

Invisible Un-removable Field: A Search by Ultra-High Energy Cosmic Rays

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A Toy model which introduces the different limiting velocities for each particle is discussed: the differentiation of the universal limiting velocity is implemented through the coupling with external tensor or vector field, something like Higgs scalar field. GZK cut-off discussion could be altered due to the violation of Lorentz symmetry.

KEYWORDS: relativity principle, High Energy cosmic rays, GZK-cut-off

1. Introduction and Summary

One can characterize an achievement of the 20-century Physics as the discovery of various symmetries, those have been hidden deep in the diversity of superficial phenomena: we can point out many symmetries such as rotational and boost symmetry of 3-space, past-future symmetry in mechanics, duality symmetry between electro- and magneto-fields, Lorentz symmetry of spacetime, discrete symmetry in atomic structure of solid, particle-antiparticle symmetry, isospin symmetry of nuclear force, chiral symmetry, "eight-fold symmetry", super-symmetry, colour symmetry and so on. Particularly, Standard Theory of elementary particles is formulated by the gauge-theory based on internal or local symmetry hidden in electro-weak and strong interactions among quarks and leptons.

However we have to remind that this unification is possible by introducing another extra idea called "spontaneous symmetry breakdown(SSB)". This mechanism is schematically written as

$$[\text{observed law}] = [\text{symmetric law}] \times [\text{SSB}].$$

New paradigm introduced here is that the observed law is separated into two different laws one is an ideal "symmetric law" and the another is to locate our universe in a non-universal particular state. Therefore, the symmetric law itself can not make in existence in our universe.

In the Standard Theory, this SSB mechanism is controlled by the external field called Higgs field: our universe has been permeated by this external field and the interaction of particle with it gives a mass. Essential difference of the Higgs field from a conventional fields of particles is that it is un-removable from our universe. The Higgs external field is a "visible

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field” through the particle’s mass.

This SSB has introduced a new ingredient about the concept of physics law, that is, the physics law itself is symmetric but our actual universe is not in a state of exact symmetry. This may be re-phrased also as followings; physics law is universal but our universe is not universal entity, or, physics law itself does not exhibit its original form in our universe where we live in. We call this kind of idea as the SSB paradigm.¹⁾ The SSB paradigm describes our universe as ”un-universal” universe.

In fact, some symmetries are not exact but show a tiny breakdown, like in case of CP-asymmetry. The actual composition of cosmic matter does not obey the particle-antiparticle symmetry in spite of CPT-symmetry in physics law itself. Following these considerations, we are tempted to think that any symmetry might be not exact in this actual universe, which has come into an existence through various spontaneous selections of non-universal parameters.

Lorentz symmetry claims that there is no preferential inertia frame. However, our actual universe is filled with the CMB and cosmic matter and we can clearly identify the preferential frame, which we have called the C-frame. Since this C-frame is approximately identical with CMB isotropic frame, the C-frame is supposed to be selected during the reheating phase at the Inflation, that is, in association with some SSB of vacuum state in quantum field theory. Some physical parameters of particles in ”our universe” is supposed to have been built through this dynamical process of the SSB.

Our speculation in this report is extend this SSB paradigm into the creation of spacetime of ”our universe”. If the spacetime of ”our universe” is a product of the various dynamical processes, it would be very natural to expect a breakdown of original symmetry of spacetime. That is a spontaneous breaking of exact Lorentz symmetry. According to some Toy models of the SSB for Lorentz symmetry, we could suppose that each particle gets their different limiting velocity: the maximum velocity at infinity energy for massive particle. We will discuss such Toy model later in this report, where the SSB is implemented by an ”invisible un-removable” field.

Lorentz symmetry, however, has been built in all fundamental concepts of modern physics, such as Dirac field, spin, renormalization group of quantum field theory, and so on. Therefore, the violation of this symmetry can not be introduced so easily. One of the claim of the relativity principle is the equivalence of all inertia frame. However this equivalence has not been directly proved so much. Only the accelerator experiments has proved this equivalence up to some Lorentz factor of $\gamma_{\text{acce}} \sim 10^5$.

In this respect, the GZK cut-off²⁾ has an unique status for the experimental verification of this equivalence. In 1972, I discussed this point and wrote a paper with the title ”Ultra-high Energy cosmic rays, Hot universe and Absolute reference frame”.³⁾ By this GZK cut-off, we will be possible to check the validity limit of the relativity principle up to $\gamma_{\text{GZK}} \sim 10^{11}$. Following

to the above Toy model, this verification can be regarded as a check of the universality of the limiting velocity. And if there were not the GZK cut-off, that may imply a finding of a unremovable hidden external field of vector or tensor type external field in addition of "scalar" type Higgs field.

2. Comoving Frame in the Expanding Universe and Relativity Principle

In our expanding universe, we can easily identify preferential inertia frames: (1)rest frame of baryon matter, (2)rest frame of astronomical objects, (3)frame in which CMB is isotropic, (4) frame in which the Hubble flow is observed isotropic. Furthermore, these four frames are approximately identical within a relative velocity difference of several hundreds km/sec. These inertia frames have a concrete physical effect in a process of the structure formation in the expanding universe.^{4,5,6)}

According to theoretical view, these cosmological frames are considered to have the same physical origin; spontaneous selection of the inertia frame at the SSB of the quantum vacuum. However, even in the vacuum universe without material substance, the creation of the expanding universe itself is the broken state of Lorentz invariance. That is a formation of comoving frame perpendicular to the time direction. We call this cosmological and comoving frame as C-frame.

In spite of a lucid existence of the C-frame, however, the Lorentz symmetry is supposed to hold in any local physical phenomena. The relativity principle does not respect this lucid existence. That is the spirit of the relativity since Galileo. In the derivation of GZK cut-off, the relativity principle is used as usual but its situation is very special because the Lorentz factor relative to the C-frame is as large as $\gamma \sim 10^{11}$, which is far beyond the Lorentz factor in the particle accelerators of about $\gamma \sim 10^5$.

Here we should not confuse the two meanings of "high energy". One is an invariant energy(or center of mass energy) defined such as ,

$$p^\mu p_\mu = E^2 - P^2 = Q^2$$

, where p^μ is total four momentum of the system. Another one is energy relative to a specific reference frame and it will be defined in the following manner as

$$N^\mu p_\mu = 1 \cdot E - 0 \cdot P = E$$

, where N^μ is the four vector which specifies this particular reference frame. For the C-frame in the expanding universe, the component is given as $N^\mu(1, 0, 0, 0)$. The Relativity principle claims that the cross section of collision, σ , does depend solely on Q but does not depend on $N^\mu p_\mu$, such as $\sigma(Q)$ but not as $\sigma(Q, N^\mu p_\mu)$. In my early paper,³⁾ the cut-off function in the momentum space was assumed to depend on $N^\mu p_\mu$ and the cross section involved to the GZK cut-off could be modified; the cut-off in the momentum space does affect the final state

integral.

The GZK cut-off, Q is $\sim 10^{8.5}\text{eV}$, which is rather low energy in high-energy physics, but, $N^\mu p_\mu \sim 10^{20}\text{eV}$ is extraordinarily large even in high-energy physics. The uniqueness of the GZK cut-off lies on the largeness of $N^\mu p_\mu$. Therefore, we should not confuse with the so-called energy frontier in the high-energy physics, e.g., Energy frontier for supersymmetry, GUT, Planck scale, etc.. Those are talking about large Q but not on the largeness of $N^\mu p_\mu$.

3. A Toy Model for Violation of Lorentz Symmetry

We discuss a Toy model which introduces the differentiation of the universal limiting velocity by the SSB.⁶⁾ Consider the following Lagrangian for a Dirac particle A,

$$L_A = \frac{i}{2} \bar{\psi} \gamma_\mu \partial^\mu \psi - \alpha_A \phi \bar{\psi} \psi + \frac{i}{2} g_A F_{\mu\nu} \bar{\psi} \gamma^\mu \partial^\nu \psi,$$

where ψ is the Dirac field of A-particle, ϕ is Higgs scalar field with coupling coefficient α_A and $F_{\mu\nu}$ is a tensor field with coupling coefficient g_A . The first term in the right hand side is kinetic term and the second one is the Yukawa coupling term which creates mass by Higgs mechanism. In this Lagrangian, the dynamical parts of ϕ and $F^{\mu\nu}$ has been omitted and ϕ and $F^{\mu\nu}$ are both taken as an external field. These external fields are "un-removable" from our universe. Non-zero value of $\langle \phi \rangle$ gives the mass, $m_A = \alpha_A \langle \phi \rangle$, to this Dirac particle.

Next we assume that some component of the tensor field has got some non-zero value as followings,

$$\langle F^{00} \rangle = B \neq 0 \quad \text{and} \quad \langle F^{\mu\nu} \rangle = 0 \quad \text{for other components.}$$

B is supposed to be nearly constant in conventional physical scale of spacetime, but it can be slowly changing with cosmological spacetime scale. This B is "un-removable" field. Then the dispersion relation for plain wave is given as⁷⁾

$$p^\mu p_\mu - m_A^2 c^2 = -2g_A B (E/c)^2$$

, where only the first order terms of B has been retained and the higher term of B has been neglected.

This relation is rewritten by denoting the three momentum as p as

$$(1 + g_A B) (E/c)^2 = p^2 + m_A^2 c^2,$$

where c is the universal constant introduced at the definition of the spacetime length by space length and time length.

Renormalizing the velocity and mass as followings

$$c_A^2 = \frac{c^2}{1 + g_A B} \quad \text{and} \quad m_{AB}^2 = (1 + g_A B)m_A^2,$$

the conventional energy-momentum relation is resumed⁶⁾

$$E^2 = p^2 c_A^2 + m_{AB}^2 c_A^4.$$

but now c_A is depending on particle species through g_A , that is, the limiting velocity, velocity in the limit of $E \rightarrow \infty$, is depending on the particle species.

Here we remark some difference between the Higgs scalar ϕ and the tensor external field $F^{\mu\nu}$. Since the value of tensor components is dependent on the choice of the inertia frame, we have adopted the C-frame as the preferential frame and the above energy-momentum relation holds only in the C-frame. This is different from the case of a scalar field, where the value of external field is independent from the inertia frame.

If we modified the Lorentz transformation with psudo-Lorentz factor

$$\gamma_A = \frac{1}{\sqrt{1 - \left(\frac{v}{c_A}\right)^2}} \quad \text{instead of} \quad \gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}},$$

the above relation keeps its form. However the Lorentz invariance apparently breaks down if we consider a system consisting of pariticles of different species. That is, Violation of Lorentz symmetry has been introduced through the differentiation of the limiting velocity for each species of particles.

The perturbative super string theory has suggested an existence of various hidden fields such as the above tensor field. If we assume a vector field A_μ in stead of $F_{\mu\nu}$ as the external field, the Lagrangian is written,⁹⁾

$$L_A = \frac{i}{2} \bar{\psi} \gamma_\mu \partial^\mu \psi - m_A \bar{\psi} \psi - f_A V_\mu \bar{\psi} \gamma^\mu \psi.$$

, where the Higgs term is now rewritten by the mass term. Here we assume

$$\langle V_0 \rangle = V \neq 0 \quad \text{and} \quad \langle V_\mu \rangle = 0 \quad \text{for all other components}$$

This V is also "un-removable" field. The the dispersion relation becomes like

$$E^2 - p^2 c^2 - m_A^2 c^4 = -2f_A V E.$$

If we define as

$$c_A(E) = \frac{c}{1 + \frac{f_A V}{E}}, \quad m_{AV}^2 = (1 + f_A V/E)^2 [m_A^2 + (f_A V)^2/c^4],$$

the above dispersion relation resume a pseudo-conventional form like

$$E^2 = p^2 c_A(E)^2 + m_{AV}^2 c_A(E)^4.$$

$c_A(E)$ has anomaly in the limit of $E \rightarrow 0$ but this limit would need a quantum mechanical correction. The violation of Lorentz invariance would dominate in the vector case similar to the scalar or Higgs case. Then the tensor case is necessary as the toy model which exhibits the violation of Lorentz invariance in the limit of large γ

4. "Miss Conduct" of Lorentz Transformation

Here we mention the two types of Lorentz transformation, those are often confused each other. One is the boost particle-transformation and the another one is the Lorentz transformation.¹⁰⁾ The Lorentz transformation is just a change of reference frame for the description of the same phenomena, which is sometime called "passive" transformation. In contrast to this, the boost particle-transformation is "active" transformation, where particle's energy-momentum are changed actually. Relativity principle claims that the boosted state and the original state seen from the transformed reference frames are identical. For the system of particles, this classification has no particular useful meaning.

However some complication comes in, when the system consists of particles and external given field. In the Lorentz transformation, both the particle's energy-momentum and the components of the external field are both transformed. Therefore the relative relation between particle and external field does not change. In the boost particle-transformation, however, particle's energy-momentum are transformed but the field configuration is kept unchanged. Therefore particle states relative to the field are different. The actively boosted state of particle is not identical with the passively Lorentz transformed state having the same particle state but different field configuration. Thus we call this situation as an "apparent" violation of Lorentz invariance. We can even say that the boost particle-transformation is in fact a misconduct of the Lorentz transformation.

What we have done in the previous section is something like this misconduct. In the actual universe, the external fields like $F^{\mu\nu}$ are totally unknown to us upto now and "misconduct" of application of the Lorentz transformation could happen. Conversely we also say that the apparent violation implies a finding of the hidden external fields and the genuine Lorentz symmetry for the total system (particle and external field) could recover.

5. Different Limiting Velocities and GZK cut-off

Without touching on any origin of different limiting velocities, we can rise a question how much degree the universality of limiting velocity has been checked by direct experiment. The assumption of non-equality of the limiting velocity of a charged particle and light velocity is equivalent to the introduction of the Lorentz non-invariant term of the electromagnetic field into the Lagrangian.¹¹⁾ In general, this is true for any non-universal assumptions of the limiting velocity.¹²⁾

Coleman and Glashow also discussed this assumption, firstly in order to explain the neu-

trino oscillation.¹³⁾ They also pointed out that the high-energy phenomena might disclose an apparent degeneracy of limiting velocity and reveal a splitting into a fine structure of the limiting velocity. They called various limiting velocity as eigen state of velocity for each particle. They have shown also that this modification does not hurt the standard theory of interaction based on the gauge field theory.¹²⁾

If the limiting velocity is dependent on the particle species A like c_A , the GZK cut-off discussion is modified very much. By the head-on collision between the cosmic-ray proton and the CMB photon, Δ particle is produced if the following condition is satisfied.⁷⁾

$$(E_p + E_\gamma)^2 - (p_p + p_\gamma)^2 c_\Delta^2 > m_\Delta^2 c_\Delta^4,$$

while the proton obeys to $E_p^2 = p_p^2 c_p^2 + m_p^2 c_p^4$. In the situation of $E_p \gg m_p c_p^2$ and $|c_\Delta - c_p| \ll c_p$, the condition becomes as followings

$$-\frac{c_\Delta - c_p}{c_p} E_p^2 + 2E_p E_\gamma > \frac{m_\pi^2 c^4}{2}$$

In the conventional case, $c_\Delta - c_p = 0$ and the threshold energy is obtained $E_p > m_\pi^2 c^4 / 4E_\gamma$.

If $(c_\Delta - c_p) \neq 0$, the above equation gives a quite different result; the cut-off disappears for $(c_\Delta - c_p) > 0$ and the cut-off energy decreases compared with the GZK cut-off for $(c_\Delta - c_p) < 0$. For example, the above equation does not have solution if

$$\frac{c_\Delta - c_p}{c_p} > 2 \left(\frac{E_\gamma}{m_\pi c^2} \right)^2 \sim 10^{-22},$$

the cut-off does not exist.

On the other hand, for $(c_\Delta - c_p) < 0$, the cut-off energy is modified as

$$E_{GZK} \left[1 - \frac{|c_\Delta - c_p|}{2c_p} \left(\frac{m_\pi c^2}{E_\gamma} \right)^2 \right] \quad \text{for} \quad \frac{|c_\Delta - c_p|}{2c_p} \left(\frac{m_\pi c^2}{E_\gamma} \right)^2 < 1$$

and

$$\sqrt{\frac{c_p}{2|c_\Delta - c_p|}} m_\pi c^2 \quad \text{for} \quad \frac{|c_\Delta - c_p|}{c_p} m_\pi^2 c^4 \gg E_\gamma^2$$

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